

NAS155:3075

JUN 15 1990

NASA Conference Publication 3075

SeaRISE: A Multidisciplinary Research Initiative To Predict Rapid Changes in Global Sea Level Caused by Collapse of Marine Ice Sheets



*Proceedings of a workshop held in
College Park, Maryland
January 23-25, 1990*



NASA

SeaRISE: A Multidisciplinary Research Initiative To Predict Rapid Changes in Global Sea Level Caused by Collapse of Marine Ice Sheets

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Proceedings of a workshop cosponsored by the
National Science Foundation, Washington, D.C.,
and the National Aeronautics and Space
Administration, Washington, D.C., and held in
College Park, Maryland
January 23-25, 1990



National Aeronautics and
Space Administration
Office of Management
Scientific and Technical
Information Division

1990

Table of Contents

	Page
Foreword	v
Workshop Participants	vi
Acknowledgements	vii
Map	viii
1. Executive Summary	1
2. Role of the Polar Ice Sheets in Climate Change	4
3. Marine Ice Sheets and Their Potential Instability	5
4. The SeaRISE Initiative	7
4.1 Goal and Objectives	7
4.2 Multidisciplinary Basis	7
4.3 Geographical Focus: West Antarctica	8
4.4 Key Scientific Questions	8
4.4.1 Glaciology: Ice Dynamics	8
4.4.2 Glaciology: Ice Core Stratigraphy	11
4.4.3 Meteorology	13
4.4.4 Oceanography	16
4.4.5 Geology and Geophysics	18
4.5 Connections with Other Research Programs	20
4.5.1 Siple Coast Project	20
4.5.2 Antarctic Geophysical Initiative	21
4.5.3 Global Ice Core Research Program	21
4.5.4 International Geosphere-Biosphere Program	22
4.5.5 Antarctic Programs of Other Nations	22
4.5.6 Satellite Programs	23
4.6 Feasibility	23
4.7 Working Group	24
4.8 Plan of Action	24
4.9 Budget	25
5. Supporting Statements from Scientific Panel Reports	26
5.1 <u>Our Changing Planet: The FY 1990 Research Plan. The U.S. Global Change Research Program</u> , Interagency Committee on Earth Sciences, 1989	26
5.2 <u>Earth System Science, A Closer View</u> , NASA Advisory Council, 1988	26
5.3 <u>The Role of Antarctica in Global Change, Scientific Priorities for the International Geosphere-Biosphere Program (IGBP)</u> , Scientific Committee on Antarctic Research Steering Committee for the IGBP, 1989	27

5.4	<u>Glaciers, Ice Sheet, and Sea Level: Effects of a CO₂-Induced Climatic Change</u> , National Research Council (NRC), 1985	27
5.5	<u>Environment of West Antarctica: Potential CO₂-Induced Changes</u> , NRC, 1984	28
5.6	<u>U.S. Research in Antarctica in 2000 A.D. and Beyond, A Preliminary Assessment</u> , NRC, 1986	28
5.7	<u>Antarctic Solid-Earth Sciences Research: A Guide to the Next Decade and Beyond</u> , NRC, 1986	29
6.	References	30
7.	Appendices	33
A:	Executive Summaries of Related Research Programs	33
A.1	<u>Science Plan for the Siple Coast Project</u>	35
A.2	<u>A Plan for a United States Program to Study the Structure and Evolution of the Antarctic Lithosphere</u>	37
A.3	<u>U.S. Global Ice Core Research Program, West Antarctica and Beyond</u>	40
A.4	<u>Satellite Remote Sensing for Ice Sheet Research</u>	42
B:	Addresses of Workshop Participants	43

FOREWORD

This document reports the results of a workshop that met on 23-25 January, 1990, in College Park, Maryland, to discuss the role of the polar ice sheets in global climate change. It was convened in response to a recommendation that emerged from a briefing of the National Science Foundation's Division of Polar Programs on May 5, 1989, regarding the findings of recent field investigations that the Siple Coast region of the West Antarctic ice sheet is experiencing major and rapid changes. The workshop participants, 32 scientists spanning all disciplines concerned with the physical environment of Antarctica, came to agreement that the single, most important aspect of the ice sheets' involvement in climate change is the potential of marine ice sheets to cause a rapid change in global sea level. During the 3-day workshop, this issue was thoroughly discussed from the diverse perspectives of glaciology, meteorology, oceanography, paleoclimatology, ice-sheet stratigraphy, glacial geology, and solid-earth geophysics. The discussions made the group conscious of the many interactions among ice, ocean, atmosphere, and lithosphere that are involved in determining how the marine ice sheets participate in climate change and that need to be understood in order to assess the magnitude of the problem of sea-level rise.

The workshop attendees concluded that the possibility of an impending rapid rise of sea level due to the response of the West Antarctic ice sheet to climate warming, or to a delayed internal instability from previous climatic changes, is serious enough that a research initiative should be created. Such an initiative must foster a rigorous evaluation of this possibility with active involvement from the full spectrum of relevant disciplines and with strong multidisciplinary cooperation. The proposed initiative is designated "**SeaRISE**" (Sea-level Response to Ice Sheet Evolution) and is described in this report.

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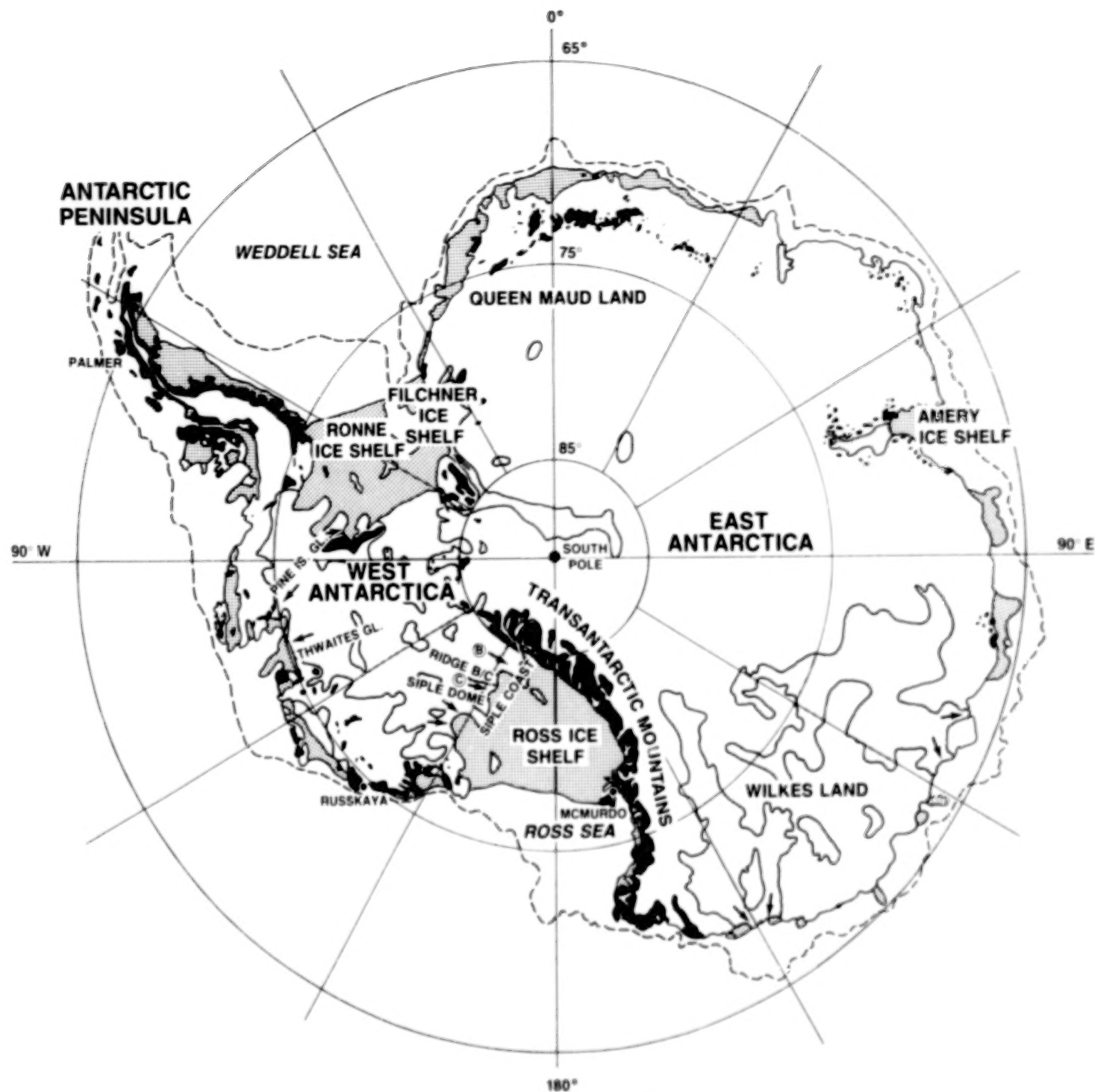
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Note: Full addresses for the participants are listed in Appendix B.

ACKNOWLEDGEMENTS

All workshop participants are thanked for their contributions to this report. Many others who, for one reason or another, could not attend the workshop also provided valuable input to this final report. Financial support was provided by the National Science Foundation/Division (NSF/DPP) of Polar Programs under grant DPP-9001579.



Map of Antarctica showing locations of features mentioned in this report. Light-shaded areas indicate portions of ice sheet grounded on bedrock more than 500 meters below sea level and represent the major portions of marine ice sheet. Arrows represent major ice streams which drain the marine ice-sheet regions. Heavily-shaded areas show ice shelves that buttress ice flow and beneath which ocean circulation is an important process of mass exchange. Solid areas represent exposed rock where glacial geology is possible. The dashed line represents the edge of the continental shelf and defines the region between the ice-sheet margin and the shelf edge where sediment cores can contribute historical information on the behavior of the ice sheet. Solid circles show the location of stations mentioned in the text.

1. EXECUTIVE SUMMARY

Concern over impending rise of global sea level due to the effect of climatic warming on polar ice sheets calls for a concerted appraisal of the marine ice sheets (those grounded well below sea level), which have the greatest potential to cause rapid and economically injurious sea-level rise. This potential stems from the marine ice sheets' inherent instability to grounding-line retreat and from the capability of their fast-flowing internal ice streams to rapidly disperse the ice into the surrounding oceans, resulting in ice-sheet "collapse." It needs to be determined whether the atmospheric and oceanographic changes involved in climatic warming are coupled to the ice sheets in a way that could cause such collapse, particularly in the large West Antarctic ice sheet, whose total collapse would raise global sea level by 6 meters. Assessing the future behavior of the ice sheets requires consideration of the coupled atmosphere-ocean-cryosphere-lithosphere system because the ice sheets are active participants in the global climatic regime and can influence climate as well as respond to it. Rapid changes recently observed to be occurring in the West Antarctic ice sheet indicate possible instability and spur an urgent effort to understand the coupled system so as to predict its future behavior.

For the above reasons, the workshop participants advocate the creation of a research initiative, called SeaRISE, that will lead toward an ability to predict the contribution of marine ice sheets to rapid changes in global sea level over the coming decades and few centuries. The name SeaRISE stands for Sea-level Response to Ice Sheet Evolution.

To be able to predict ice-sheet evolution, the initiative must develop an understanding of the current state, history, internal dynamics, and mutual interactions within the polar atmosphere-ocean-cryosphere-lithosphere environmental system and its coupling to global climate. Much of the supporting research needed to develop this understanding is multidisciplinary in nature, as is the ultimate synthesis of the results in formulating a prognosis of sea-level change. The essential role of SeaRISE is to foster and guide the multidisciplinary approach and to see to it that disciplinary components are well integrated into the program.

Research within SeaRISE will concentrate on the West Antarctic ice sheet because it has the greatest potential contribution to rapid sea-level change. Elements of the needed research program are expressed in terms of the key questions that need to be answered to achieve the initiative's goal. In condensed form, these are:

- * What are the current local and regional net mass balances of the ice sheet and how are they realized in the balancing of input from the atmosphere against output via the ice-sheet flow system and the ocean?

- * What are the physical controls on the motion and areal extent of the ice streams, and how are these coupled to climatic factors and incorporated into the complete dynamics of the ice-sheet/ice-shelf system?

- * How has the configuration of the West Antarctic ice sheet responded to climatic changes over the past glacial/interglacial cycle and has it undergone episodic rapid mass wasting?

- * What are the causes of precipitation over the ice sheet, the temporal variations of these processes in the context of global atmospheric circulation, and the precipitation trends occasioned by climate change?

- * How will climate change affect the ocean state and distributions of sea ice around Antarctica, with consequent effect on precipitation over the ice sheet?

- * What is the mass-exchange interaction between the ice shelves and the underlying ocean water and how will this be affected by climate change, with resulting change in mass balance of the ice-shelf/ice-sheet system?

Once these questions can be answered in sufficient detail and with sufficient reliability, it will become possible to model the coupled atmosphere-ocean-cryosphere-lithosphere system and to test the modeling against a known history of ice-sheet evolution. Successful modeling will then provide the basis for predicting future evolution.

A head start on some aspects of SeaRISE within individual disciplines is already underway in current or proposed projects and programs involving the West Antarctic ice sheet: the Siple Coast Project, the Antarctic Geophysical Initiative, the Global Ice Core Research Program, the International Geosphere-Biosphere Program, various satellite remote-sensing missions, and research programs of other nations. The unique role of the SeaRISE initiative is to unite these various elements, together with consciously multidisciplinary projects not yet launched, in support of the important goal of predicting the future evolution of marine ice sheets.

The needed research tools are largely in hand, so that the feasibility of reaching the supporting objectives is assured. Attainment of the ultimate goal of predicting ice-sheet evolution is therefore possible. The execution of SeaRISE would consist of an initial 5-year study of the Ross Embayment region of West Antarctica while reconnaissance data were collected of other marine ice-sheet areas in East and West Antarctica and possibly in Greenland. This would be followed by a second study phase, also lasting approximately 5 years, concentrating on those other marine ice-sheet areas that indicate particular susceptibility to collapse.

2. ROLE OF THE POLAR ICE SHEETS IN CLIMATE CHANGE

The polar ice sheets are the primary reservoir of the world's fresh water, containing enough ice that, if released into the oceans either by melting or as icebergs, global sea level would rise by 70 meters. Even a 1% decrease in ice-sheet volume would have a major impact on coastal areas throughout the world. The severity of the impact increases with the rapidity of the sea-level rise. A rise of 1 meter in 100 years would have a very damaging effect on the international economy as well as a severe ecological impact. Studies by the National Research Council (Committee on Glaciology, 1984, 1985) have brought into focus the problems of assessing the magnitude and rapidity of the sea-level rise that should be anticipated in connection with potential worldwide climatic change. An attack on these problems has been urged as part of the U.S. Global Change Research Program in a report of the Interagency Committee on Earth Science (1989). Detailed statements from these reports are quoted in Section 5, below.

A particularly rapid rise in sea level would occur if a substantial part of the polar ice sheets were to disperse rapidly into the adjacent oceans, a process that has been called ice-sheet "collapse." Such events occurred in large ice sheets at the end of the last ice age, about 10,000 years ago. The question is, are any of the remaining ice sheets subject to the possibility of such a collapse either as a result of anticipated climatic warming or as a delayed internal instability triggered by past climatic fluctuations?

It is important to correct any impression that the polar ice sheets will respond only passively to climatic change. They are active components of the world climate system and will participate actively in changes of that system. Their participation is exercised through strong couplings between the ice sheets and the atmosphere, and between the ice sheets and the adjacent oceans. The large Antarctic ice sheet, in particular, is strongly coupled to the Southern Hemisphere's atmosphere-ocean system. The famous outward-directed katabatic winds generated by radiative cooling over the ice sheet force a continent-scale atmospheric circulation that couples with atmospheric behavior in mid-latitudes and even in the tropics. The formation of sea ice around the continent, promoted by the outward flow of cold air, generates cold, saline bottom water that spreads into all ocean basins and strongly influences the global oceanic circulation. Because of such couplings, assessing future ice-sheet behavior and its effect on global climate is a problem that requires understanding of feedbacks far more complex than a shift in the relative areas of net accumulation and net melting driven by changes in local temperature. The importance of atmosphere-ocean-cryosphere interactions in climatic change has been emphasized in the NASA program of Earth System Science (1989).

3. MARINE ICE SHEETS AND THEIR POTENTIAL INSTABILITY

There is a class of ice sheets believed to be inherently unstable and prone to rapid collapse. They are termed "marine ice sheets" and are characterized by being grounded on beds well below sea level. Typically, they go afloat around their peripheries at the grounding line, beyond which the ice is too thin to maintain contact with the bed. Some very large floating ice masses are formed in this way, most notably the Ross, Ronne, and Filchner Ice Shelves (see Map). The potential instability arises in cases where the bed becomes progressively deeper inland from the grounding line. If ice at the grounding line thins, the grounding line would have to retreat inland. By doing so, ice at the new grounding line would find itself in deeper water, where the ice needs to be thicker to maintain contact with the bed. Unless the ice there can be supported by a "buttressing" effect of the floating ice shelf beyond the grounding line, it will tend to thin with increasing rapidity as the grounding line retreats upstream, causing an unstable condition in which the grounding line retreats faster and faster as the entire ice mass is progressively dispersed toward its margin and into the ocean. This process is what is meant by the term "ice-sheet collapse." Any process that initiates a retreat of the grounding line could be a possible trigger of collapse. Possible triggers include rising sea level and thinning ice shelves caused by increased sub-shelf melting or enhanced calving. Because of this potential instability, glaciologists believe that marine ice sheets have the capacity to show a larger and faster response to climatic fluctuations than do continental ice sheets; those whose beds are above or near sea level and do not deepen inland, as is the case with much of the East Antarctic ice sheet (see Map).

A major element of the ice-sheet collapse mechanism is the motion of what are called ice streams, large river-like currents of ice flowing through the ice sheets much faster than the general motion. Some 30 to 80 kilometers wide and 300 to 500 kilometers long, ice streams flow at speeds of up to 1 kilometer per year or more, while normal ice-sheet movement is only a few meters per year. Ice streams have the potential of dispersing the ice-sheet mass much more rapidly than is possible with normal flow mechanisms. The collapse potential of an ice sheet thus depends greatly on how quickly a system of ice streams could develop in it, and how extensive and fast-moving these ice streams would be.

Although the concept of marine ice-sheet instability and collapse was originally a theoretical one, results of recent Antarctic field work support the assumptions and reasoning on which it is based. A closely related concept, the potential for unstable retreat of tidewater glaciers, has been verified dramatically by the onset of unstable retreat of Columbia Glacier, Alaska, during the last 10 years. Also, evidence from glacial geology and paleoclimatology now points to collapse of major portions of the North American ice sheet at the end of the last

ice age. The collapsing portions were marine in character and were subject to the instability conditions noted above.

The West Antarctic ice sheet is the largest surviving marine ice sheet in the world. Its deep, basin-shaped bedrock floor has the geometry appropriate for instability, and it is believed by some to have collapsed and disappeared during the last interglacial period about 125,000 years ago. More certain is the fact that during the last glacial maximum this ice sheet was much larger, extending in places to the edge of the continental shelf. In the last 18,000 years it has retreated to a position well back of that maximal stand. Currently, we do not know whether it is continuing to retreat or has finished retreating and is readvancing. Further, we have no idea what is the overall current rate of change of the West Antarctic ice sheet. Direct indications of currently unstable behavior have recently been discovered in the form of abnormally rapid changes taking place along the Siple Coast (see Map) (SCP Steering Committee, 1988). Measurements of net mass balance in other regions of the ice sheet indicate a complex pattern of growth and wastage, but only a small portion of the total ice-sheet area has been measured. The presence of five active ice streams feeding ice from the interior of West Antarctica into the Ross Ice Shelf, and other ice streams draining other portions of West Antarctica into the Ronne Ice Shelf and separate peripheral ice shelves on the northern boundary of the ice sheet (see Map), may be manifestations of collapse already underway. The current absence of a substantial ice shelf that could buttress the Pine Island and Thwaites Glaciers could cause a forthcoming collapse of that part of the ice sheet.

The question facing us is whether the atmosphere and ocean system is coupled to the ice sheets in such a way that a climatic warming from present conditions is likely to trigger, or has already triggered, the marine ice-sheet instability in the West Antarctic ice sheet, or in certain parts of the Greenland or East Antarctic ice sheets that are marine in character. Answering this question requires a better understanding of the interactions between the marine ice sheets and the global environment than has yet been developed.

The instability/collapse response, involving unstable grounding-line retreat, ice-shelf buttressing, ice-stream drainage, and the coupling of these processes to atmospheric, oceanographic, and lithospheric processes, is a dynamic system response quite distinct from, and far more complicated than, a quasi-static response in which climatically induced changes in snowfall, ablation, and calving result in slow growth or shrinkage of the ice mass. Thus a far greater level of effort and breadth of interdisciplinary contribution are required to assess the potential for the instability/collapse response.

4. THE SeaRISE INITIATIVE

For the reasons just given, current attempts to assess or predict impending climatic change and its major consequences should include a concerted and systematic effort, coordinated across the relevant disciplines, to predict the course of ice-sheet evolution as an integral part of the foreseeable future of global climate. The workshop participants urge the creation of a research initiative for this purpose. The initiative would provide the impetus to undertake a coordinated suite of investigations attacking the several problems that must be solved to make an unequivocal prediction of the future of marine ice sheets, as outlined below. The initiative would also provide, through a management structure developed under its aegis, central coordination and integration to keep the component investigations moving concertedly toward the common goal of making the needed prediction of ice-sheet evolution. We have chosen a name for this initiative that serves as a reminder of its importance: **SeaRISE** -- Sea-level Response to Ice Sheet Evolution.

4.1 Goal and Objectives

The goal of SeaRISE is to predict the contribution of marine ice sheets to rapid changes in global sea level in the next decade to few centuries.

Because ice sheets occur in an interacting environmental system of polar atmosphere, polar oceans and the Earth's crust, there are a number of supporting objectives which must be met to attain the above goal.

The objectives of SeaRISE are to understand the current state, internal dynamics, interactions, and history of this environmental system.

4.2 Multidisciplinary Basis

Some of the needed elements of the SeaRISE initiative within individual disciplines are already underway in current or proposed projects and programs, as detailed in Section 4.5. What the SeaRISE initiative especially adds to globally significant investigations related to ice-sheet evolution is the emphasis on multidisciplinary research, in recognition of the highly interactive polar environment. SeaRISE will concentrate on the important interactions and feedbacks among the major environmental components: the ice sheets, the terrains on which they move, the oceans which supply and remove mass, and the atmosphere which delivers the mass. SeaRISE is an initiative for the comprehensive study of a complete environmental system.

4.3 Geographical Focus: West Antarctica

SeaRISE will focus on the West Antarctic ice sheet because it is the largest remaining marine ice sheet, containing enough grounded ice to raise sea level 6 meters, and because it is known to be changing rapidly now (Section 3). This combination of characteristics identifies the West Antarctic ice sheet as the ice sheet with the greatest potential for rapid sea-level rise. SeaRISE will be able to build upon the substantial body of existing data of the West Antarctic ice sheet and utilize these data in new ways from the perspectives of interdisciplinary processes as discussed below.

There are parts of other ice sheets, however, that are also marine in character and, therefore, may hold the same, or greater, potential for collapse. A large portion of the East Antarctic ice sheet in eastern Wilkes Land is grounded on the Wilkes Subglacial Basin, well below sea level (see Map). In Greenland, Jakobshavns Glacier drains about 10% of the Greenland ice sheet through a deep channel whose floor is also well below sea level. To deliver a complete prediction of the potential contribution of all marine ice sheet regions to rapid sea-level rise, SeaRISE will need to consider these areas outside of West Antarctica. It is, however, the judgement of the workshop that the focus should initially be on the West Antarctic ice sheet.

4.4 Key Scientific Questions

The research needed to achieve the goal of the SeaRISE initiative and its supporting objectives is outlined here in terms of the key scientific questions that need to be answered. The questions are presented in disciplinary groupings for convenience of recognition by funding sources and by individual scientists, who relate naturally to their particular disciplines. However, as indicated in Section 4.2, the content of most of the questions is multidisciplinary. SeaRISE will emphasize a multidisciplinary approach to these questions and to the final synthesis of their answers in predicting how the evolution of marine ice sheets will affect global sea level over the coming decades and few centuries.

4.4.1 Glaciology: Ice Dynamics

1) What is the present distribution of surface-elevation change, and what is the net mass balance of the West Antarctic ice sheet?

Results from the Siple Coast Project show that a major West Antarctic ice stream, Ice Stream B (see Map), has a substantially negative mass balance and is changing actively, while the adjacent Ice Stream C has a substantially positive

mass balance. The large local variations in mass balance revealed by these results make it imperative to determine the overall mass balance of the ice sheet so as to ascertain the large-scale spatial distribution and temporal variability of surface-elevation change and identify possible regions of unstable behavior.

Determination of the areal distribution of elevation change will permit determination of the net mass balance, which is a direct measure of the rate at which the West Antarctic ice sheet is contributing water to the ocean, and will result in identification of the ice-stream and catchment areas that are of greatest interest in terms of flow mechanics. Surface-elevation measurements on the floating ice shelves should be included, and the grounding lines should be delineated accurately in order to distinguish the inland ice sheet, which is capable of contributing to sea-level change, from the ice shelves which are not.

Satellite altimeters provide a means for direct measurement of elevation change. Data limitations forced by an absence of altimeter-equipped polar-orbiting satellites will be removed in the early 1990's by the European Space Agency's (ESA) ERS-1 satellite which will extend radar-altimeter coverage poleward to 81 degrees latitude. Later in the decade, a laser altimeter onboard an EOS satellite platform will provide surface elevations accurate to well under a meter.

Calculation of net mass balance requires data on accumulation rates and discharge flux (from ice velocities and ice thicknesses). Accumulation rates are presently collected by surface field measurements as are most velocity measurements, while radar sounders either on the ground or from airplanes supply ice-thickness data. Techniques are under development to obtain accurate ice velocities from satellite imagery in areas of sharply defined surface features (e.g. crevasses) and passive microwave emissions are probably useful for spatial interpolation of accumulation data. Eventually, space-borne lasers will be used to determine movements of retroreflectors placed on the surface.

2) What are the physical controls on the motion and areal extent of ice streams whose flow is the dominant internal mechanism that could bring about rapid ice-sheet collapse?

The answer to this question requires an understanding of the mechanics of basal motion and the buttressing effect by ice shelves. The greatly enhanced basal motion that is responsible for the rapid flow of ice streams probably occurs by shearing of subglacial till, with possible involvement of ice sliding over bedrock in some areas. To formulate the quantitative mechanics of these processes we need to know the specific influences of basal shear stress, basal water pressure in relation to overburden pressure, basal heat generation, and the lithology and

thickness of subglacial till. We also need to understand and quantify the processes by which these variables are controlled under the ice sheet. To provide the factual basis for understanding these processes, measurements are needed of the variables in situ, via boreholes drilled to the bottom of the ice, and by seismic and radar sounding. Mechanical tests are needed to reveal the flow properties of subglacial till sampled by basal coring in boreholes.

The control exerted on ice-stream flow by ice-shelf buttressing needs to be understood quantitatively in terms of the resistance of ice-shelf pinning points (ice rises and ice rumples) and shear margins. The ice-stream/ice-shelf interaction is governed by the internal deformation mechanics: the gravitationally induced force balance within these ice masses, the longitudinal and lateral transmission of stresses, and the resultant basal shear stresses driving the basal deformation that leads to rapid ice-stream motion. The response of the ice shelves to climatic and sea-level changes is, to a large extent, governed by the interaction between the underside of the ice shelf and the ocean water below, as well as with the pinning points. An improved understanding of these interactions is needed.

Much of the work to reveal the ice-stream flow mechanism has already been undertaken in the Siple Coast Project (see Section 4.5.1). Surface-deformation surveys, seismic- and radar-reflection profiles, and direct observations in access holes drilled to the ice-stream bed have yielded a substantial increase in knowledge of the ice streams. Extension of some of these techniques to the region of ice-stream/ice-shelf interaction, to the currently inactive Ice Stream C, and to the interstream Ridge B/C (see Map) has contributed further perspective; extension of other techniques to these areas is needed. The required tools are at hand to study the dynamics of grounded ice and should be applied to the areas of ice-stream initiation. There are already sufficient data on ice velocity and deformation, including their temporal changes, to provide a basis for beginning to test numerical models of ice-stream motion that incorporate quantitative formulations of the ice-stream flow mechanism. Better techniques and further data collection are needed to study ice-shelf/ocean interactions, however (see Section 4.4.4, Question 2).

3) How will the volume of grounded ice change over the next decades to several centuries?

The answer to this question is tantamount to the prediction of the future course of sea-level change that is the goal of the SeaRISE initiative. It depends upon a synthesis of the answers to all of the key questions.

Changes in ice volume must be calculated by physical models of marine ice-sheet dynamics. These models must be constrained and tested against the

historical record of ice-sheet variations over the past 125,000-year glacial/interglacial cycle before they can be reliably used to project ice-sheet evolution decades to centuries into the future. To achieve this, field data and models are required for the Ross Sea sector, the Pine Island Glacier, Thwaites Glacier and Weddell Sea sectors, and finally the Wilkes Land region in East Antarctica (see Map), in order of decreasing urgency. Data sets from terrestrial glacial geology, marine sedimentology and micropaleontology, ice-core climatology, glacial isostasy, and current ice-sheet topography and thickness will supply the historical and contemporary constraints that are used to test the models.

Predictions of future behavior will require interactive predictions of accumulation/ablation (meteorology) and of oceanographic interaction as boundary conditions. Knowledge of ice-stream dynamics (Question 2, above) will provide the quantitative basis for flow models to simulate the temporal evolution of ice-sheet geometry.

4.4.2 Glaciology: Ice Core Stratigraphy

1) Did the West Antarctic ice sheet collapse during the previous interglacial?

The assertion that the 6-meter rise in sea level during the last major interglacial was caused by a disappearance of the West Antarctic ice sheet has been repeated so often that many believe it has been established. It has not. Recovery of interglacial ice from West Antarctica would be proof that the ice sheet did not disappear completely at that time. Even if the oldest ice proves to be younger than the last interglacial, this will not prove the disappearance of the ice sheet because geothermal heat could have removed interglacial ice. Temperature measurements on both sides of the subglacial interface would determine the rate at which ice is being melted. It is expected that if the West Antarctic ice sheet had disappeared during the interglacial period, there would be proxy indicators in a deep core of a drastically altered flow regime in which East Antarctic ice flowed northward into the West Antarctic basin.

2) What changes occurred in the atmosphere over the West Antarctic ice sheet over the last glacial/interglacial cycle and how do we interpret these changes?

Ice cores provide unique samples of past atmospheres that can be extracted from the ice and analyzed for the various chemical, isotopic, and particulate constituents and their relative amounts (ICWG, 1989). These data will help meteorologists assess the changes that occurred in the atmospheric

circulation patterns. Changes in circulation will have affected the pattern of precipitation. Comparison of these records to ice-core records from other sites around the globe will reveal whether the changes were local or global.

Annual accumulation layers can be counted individually from the surface back for hundreds to thousands of years; the length of this record depends on the magnitude of the accumulation rate and the vertical strain rate in the upper layers. These data are a direct measure of accumulation rate and its temporal variability. This is a valuable check on the meteorological characterization of the area.

3) What has been the response of the West Antarctic ice sheet to the inferred atmospheric changes and to changes in sea level?

Ice cores provide various data related to the flow nature of the ice. Crystal size, fabric and temperature all influence the effective viscosity of the ice and represent the integrated deformation and temperature history of the ice. These data are extremely useful in constraining flow models that attempt to reproduce the history of the ice sheet.

Total gas content of the air trapped in ice cores provides a measure of atmospheric pressure that existed when the ice sealed off air-filled inclusions from the atmosphere. By assuming a relation between atmospheric pressure and elevation, total-gas-content measurements can be used to infer the elevation of the ice when the inclusions were sealed. Once the core is dated, the total-gas record gives a history of the surface elevation at, and upstream of, the core location.

There remain some ambiguities in the elevation record derived from total-gas-content data. Large changes in the shape of the ice sheet or significant changes in the atmospheric circulation pattern could alter this relation and force adjustments of the interpretation of the total-gas-content record. Much experience will be gained in the interpretation of total gas in cores already recovered from Greenland and East Antarctica and it is expected that the current shortcomings in this valuable technique will be eliminated in the near future.

Geophysics and geology also provide important time-series records of ice-sheet behavior, but of parameters different from those derived from ice cores. This can be used to great advantage if these geologic records can be cross-correlated with marker horizons in the ice cores through the identification of events such as temperature changes, volcanic eruptions, or alterations to atmospheric circulation. This combination of records would allow for a more complete picture of ice-sheet behavior and also serve as a check of consistency

between the interpretations of each record. For example, it would be extremely interesting if a period of rapidly decreasing surface elevation on the ice sheet correlated with a rapidly retreating ice-shelf terminus. This scenario would indicate the collapse of a marine ice sheet.

4.4.3 Meteorology

1) What is the magnitude and interannual variability of moisture transport into the West Antarctic ice sheet?

The atmospheric transport of water vapor across the coastline yields the snowfall (and thus accumulation) that feeds the West Antarctic ice sheet. This is of obvious importance in determining the current net mass balance of the ice sheet, but both the magnitude and temporal variation of this transport across the northern periphery of West Antarctica are very uncertain. The West Antarctic sector is one of the main areas of the Antarctic continent where relatively large amounts of water vapor are transported well inland because its average elevation is much lower than the East Antarctic ice mass.

Ice-sheet average and regional precipitation rates can be derived from the convergence of the moisture transport by careful evaluation of broad-scale observations. It is expected that some inferences about precipitation changes can be derived from current moisture-flux characteristics. Interannual flux variations should be related to changes in the large-scale atmospheric circulation, synoptic processes and oceanic boundary conditions, like sea-ice and sea-surface-temperature (SST) anomalies. A deeper quantitative understanding of these interactions is critical because it will allow accumulation variations, which are difficult to measure everywhere on the ice sheet, to be inferred from more viable measurements of the factors that determine the accumulation pattern.

Two key atmospheric data sources are available for diagnoses of quantities like moisture flux: numerical syntheses from global analysis centers like the European Center for Medium-Range Weather Forecasts (ECMWF) and remote sensing observations. The former data source incorporates all available observations, but suffers from the lack of conventional meteorological observations over the ocean areas to the north and over the ice sheet itself. Data assimilation studies are needed to determine how the atmospheric motions over Antarctica, in both the boundary layer and the free atmosphere, can best be described. Rational decisions can then be made as to the need for new observation sites and their locations. Without question, West Antarctica is one area where many additional observation sites are needed. One practical and effective action would be to encourage strongly the commencement of an upper-air program at the manned Russkaya Station on the West Antarctic coast (see

Map). Strategies for eliminating the West Antarctic data void are deployments of automatic weather stations on the ice sheet and on offshore islands, and of buoys in the South Pacific Ocean.

Satellite observations, particularly those at passive-microwave wavelengths, offer great potential for deriving moisture fluxes, etc., over such data-sparse areas. A substantial effort is needed to transform this potential into reality by solving such technical problems as retrieval of water-vapor profiles over sea-ice and ice-sheet surfaces. It is notable that weather-satellite data currently being collected at McMurdo and Palmer Stations provide complete coverage of West Antarctica.

2) What are the important synoptic processes that affect the moisture flux and what is the variability of each process?

Cyclonic activity causes the patterns and variability of the moisture fluxes. However, very little is known about these processes. There is a need to identify the regions and types of cyclogenesis (e.g., synoptic frontal wave, mesoscale vortices generated at higher latitudes), cyclone tracks and dissipation regions, and also their relationships with sea-ice conditions (extent and concentration) and Antarctic orography (especially katabatic drainage). Of particular importance is an examination of the frequency of and mechanisms by which cyclones penetrate deep into the ice-sheet interior. Without an understanding of these processes, it will not be possible to reliably interpret the record of past accumulation rates and atmospheric constituents derived from ice cores. The understanding of the variability of these regimes must extend over all accessible time scales: monthly, seasonal and interannual.

To answer this question of synoptic processes reliably, a relatively long (10- to 15-year) daily synoptic data base is required for the middle and higher southern latitudes. This is becoming possible with both the operational analyses of various meteorological centers (e.g., Australian Bureau of Meteorology, ECMWF) and satellite polar-orbiter data on cloud systems (visible, infrared), precipitation zones (passive microwave) and sea ice (passive microwave). Previous work has made use of relatively short conventional data bases that either cannot be directly intercompared (e.g., the 18-month International Geophysical Year and the FGGE year of 1979) or contain major data gaps over the southern Pacific Ocean or the Antarctic (e.g., the South African analyses of the 1960's). From the early 1970's, data bases have been improved with the inclusion of satellite, buoy, and automatic-weather-station data.

3) What are the patterns of large-scale variability in the atmospheric circulation?

Synoptic processes express broader scale atmospheric, oceanic and ice-sheet conditions. An understanding is needed of the dominant patterns of variability and how these processes interact in order to deduce correctly the record of past large-scale atmospheric patterns from the synoptically dominated records of individual ice cores. The connections between the large-scale and synoptic processes must be understood on time scales ranging from the weekly and seasonal (e.g., atmospheric blocking, links with tropical convection, sea-ice extent and concentration) through the interannual (El Nino Southern Oscillation [ENSO] and other teleconnections) to decadal (e.g., changes in the "mean" low-pressure centers of the Antarctic trough and ocean circulations).

As in Question 2 above, combinations of operational analyses and satellite data over at least a 10 to 15-year period should provide information on the variability of the large-scale processes and the interactions among the component parts.

4) How would the important atmospheric processes change under altered boundary conditions?

Numerical models are primary tools in the study of the atmospheric processes that determine the precipitation and other aspects of the Antarctic climate. Interactive evaluations of numerical modeling/theoretical studies and observational analyses are required to extract the maximum understanding and realism from all approaches. Understanding the important processes and their sensitivity to orographic, sea-ice and SST characteristics as well as to the CO₂ content of the atmosphere is vital for the study and prediction of the behavior of the West Antarctic ice sheet in particular, and of sea-level changes in general.

Studies using Atmospheric General Circulation Models (AGCM's) and high-resolution, regional models are needed to improve our understanding of the planetary, synoptic and mesoscale atmospheric processes over Antarctica. Incorporation into AGCM's of the knowledge gained from this section's investigations will make it possible to commence a realistic assessment of the interactions between Antarctica and global climate. Complete exploration of this topic will require coupling of AGCM's to realistic ocean and sea-ice models.

Before reliable predictions of future climatic changes can be made, however, the deficiencies of current AGCM's in simulating the present-day climate of polar latitudes must be addressed. Comprehensive evaluations of, and refinements to, the parameterizations of physical processes in polar regions are

required. Studies must be performed to determine the sensitivity of the Antarctic climate to the above-mentioned characteristics. The connection between lower latitudes and the south polar region, and in particular the influence of ENSO events, must be evaluated.

4.4.4 Oceanography

1) What are the connections between the waters of the open ocean and those on the continental shelf?

It is through the exchange of water at the continental shelf edge that the global ocean directly influences the ice-sheet environment. There is a shallow circulation cell which traverses the continental shelf and is composed of less-saline shelf waters and intrusions of warmer water from beyond the continental shelf break. The composition of these waters is also determined by their interactions with the margins of the ice sheet or ice shelf where melting can be excessive (many meters per year) and with coastal polynyas where heat and salt are vigorously exchanged with the atmosphere and sea ice. It has been suggested that rectification of tidal currents near the ice front may drive this shallow circulation.

To answer this question, the extent and current of water masses that transport varying amounts of fresh water and salt across the shelf break need to be determined. This requires standard oceanographic measurements of salinity and temperature, and perhaps other tracer constituents, on a fine spatial scale both laterally and vertically. Because temporal variability of these water masses is expected, frequent monitoring is also required.

2) What is the spatial pattern and temporal variability of ocean interaction with the ice shelves of West Antarctica?

An increase in sub-ice-shelf melting has long been believed to be a likely trigger for marine ice-sheet collapse. Sub-ice-shelf melting and freezing away from the ice-shelf front are controlled by a single, deep, thermohaline circulation cell involving inflowing high salinity shelf water (HSSW) and outflowing ice-shelf water. Large quantities of HSSW are generated as salt is rejected by sea ice forming in shore leads kept open by prevailing offshore katabatic winds and by tidal action. The physics of this circulation cell: the sinking of the HSSW, its motion along the sub-ice-shelf bottom, the melting it causes at the grounding line, and its freshening and eventual emergence from under the shelf, are all reasonably well understood. What is not understood are the spatial and temporal patterns of this circulation and where the sites of basal freezing and melting occur. These are critical because the redistribution of mass under the ice shelf

affects the pattern of shelf deformation and, through the buttressing effect, the flow of the ice sheet.

The cold, fresh water which exits from beneath ice shelves is an important constituent of Antarctic Bottom Water (AABW) which forms when this water mixes with the warmer intermediate-depth water of the Southern Ocean. AABW subsequently spreads out among all the ocean basins and becomes one of the major components of, and forcings on, the global oceanic circulation.

Hydrographic and isotopic sampling of the sub-shelf waters can be accomplished from access holes drilled through the ice shelf. The drilling and sampling technologies already exist. The challenge will be in developing the ability to recover instrumentation which, at present, is an expensive task. Long-term monitoring of the water masses that enter and exit the sub-ice-shelf cavity is a simpler measurement but only indicates the net heat exchanged between the ice shelves and the ocean, not how ice may have been redistributed. Large temporal variations have already been observed in the circulation pattern at the front of the Ross Ice Shelf. To alleviate the need for an inordinately large number of monitoring stations, it is necessary to identify the key sites where the majority of glacial meltwater enters into the deep waters of the Southern Ocean.

3) What will be the spatial and temporal patterns of climatically induced change in the sea ice and ocean state of the Southern Ocean?

General Circulation Models (GCM's) have indicated a hemispheric asymmetry in the oceanic response to atmospheric warming. This prediction is based on parameterization of the processes by which heat is taken up by the oceans; however, these processes are poorly understood and there may be additional important processes that are not included in the GCM's. Thus, it is critical that our knowledge of these processes be improved before even the broad patterns of climatic influences on the Southern Ocean suggested by the GCM's can be accepted.

4) What is the relationship between leads and polynyas in the sea ice and regional accumulation rates on the ice sheet?

Conceptually, it is known that there is a relationship between the open areas of the sea-ice pack and the accumulation of snow over the ice sheet, but details remain a mystery. Most of the Antarctic accumulation is delivered in winter storms when the open ocean lies hundreds of kilometers from the continent. Thus, the small openings in the otherwise solid sea-ice cover are important sources of moisture. By combining records of sea-ice concentration, weather patterns (both taken from satellite data sets), and records of accumulation rate

(taken from ice cores), correlations can be sought that will aid in evaluating the nature of this relationship. Parameterization of this effect will be necessary in full-scale numerical models of the West Antarctic environment.

4.4.5 Geology and Geophysics

1) What was the configuration of the West Antarctic ice sheet during the last glacial maximum; what is its configuration during a glacial minimum; and has it, or any marine ice sheet, undergone episodic rapid mass wasting?

Major fluctuations in the West Antarctic ice sheet can be established from examining widespread exposures of terrestrial sediments and areal distributions of glacial erosional features, and from geophysical studies coupled with systematic drilling in the subglacial and submarine sedimentary basins of the region. Initially it must be determined whether the ice sheet routinely advances to the edge of the continental shelf during glacial maxima and retreats completely during interglacials. Knowledge of these extremes will provide a context for studying rapid fluctuations of ice volume and will assist in establishing the amount of retreat that has occurred in the present interglacial and how long it might take for the current ice sheet to reach its minimum stand.

Drift sheets, end moraines, erratics, striations, and strandlines provide reliable constraints upon which reconstructions of past configurations of the West Antarctic ice sheet can be based. From these data, the boundaries of the ice sheet--both areal and vertical--and the flow direction can be determined. When tied to specific time intervals by relative (e.g., weathering, paleontologic) and numerical (e.g., radiocarbon, thermoluminescence) dating methods, these data contribute to a chronology of ice-sheet shrinkage and growth in addition to providing lower bounds of the rates of retreat and advance. Further investigations of the erosional surfaces and terrestrial deposits left by the West Antarctic ice sheet in the marginal areas of the Transantarctic Mountains, the Antarctic Peninsula, and in the inland areas of the Ellsworth/Whitmore crustal block and Marie Byrd Land are needed.

The geologic record can also be extended into the ocean-covered areas of the continental shelf where the ice sheets deposit material and rework this material when they advance over it. The structure and stratigraphy of this sediment furnish a record of glacial and glacial-marine conditions at the time of deposition. By dating the core material using geochemical and paleontological techniques and by evaluating the relative composition and character of these sediments, the age of key units and therefore the rates and patterns of ice-sheet retreat can be obtained.

Fresh core material is needed from the continental shelf beneath the Ross Sea, particularly in its central and eastern portions. In addition to the petrographic, paleontological and geochemical studies mentioned above, emphasis should be placed on determining the geotechnical and geomagnetic properties of this material. Furthermore, to assure sampling sequences undisturbed by icebergs and to assure that different cores have sampled the same stratigraphic interval (a characteristic absent in many of the cores previously obtained), a program of side-scan sonar and high-resolution seismic profiling should be undertaken in conjunction with this coring. As part of this geophysical effort, particular attention should be given to mapping morphological features and seismic facies that mark former grounding-line positions.

For reasons completely analogous to those above, sediment cores are also required from beneath the ice sheet in central West Antarctica and from beneath the Ross Ice Shelf. Acquisition of these samples can either be in conjunction with coring activities undertaken for primarily glaciological or oceanographic purposes or, because the benefits of these data are so great, as a dedicated program to provide access holes for subglacial sampling. As was the case for the submarine coring, subglacial coring ought to be complemented by high-resolution seismic profiling, with the addition of ice-penetrating radar studies of bedrock morphology.

Ultimately, studies which focus on the nature of the Holocene rise in sea level are needed to test the idea that the wasting of marine ice sheets caused rapid sea-level rises and to assess the impact that these changes had on coastal regions. This work is best conducted outside the Antarctic on tectonically stable continental shelves and islands. A special effort should be made to reconcile the sea-level contributions of marine ice sheets and the ice volume estimate inferred from deep-ocean sediment coring.

2) What are the geologic controls on the flow of a marine ice sheet?

To understand the formation and disappearance of the West Antarctic ice sheet and its contribution to sea level, it is necessary to understand both its physical character and its geologic setting. The englacial properties, subglacial lithology, distribution of geothermal flux and tectonic activity all must be considered.

There is evidence that the positions of the ice streams are controlled by the subglacial lithology and perhaps by the thermal regime. If their rapid motion is caused by a deforming subglacial till made weak by pressurized subglacial water, then the ice streams must be located near a readily erodible source of sediment as well as in a region characterized by basal melting. It is well known that the

West Antarctic lithosphere is characterized by recent volcanism and associated high geothermal flux but few details exist on the spatial pattern of these characteristics. Isostatic response of the bed to former ice-sheet changes may also play a role in altering the stability of the ice sheet. The anticipated vertical displacements of several hundred meters, resulting from the isostatic compensation for the larger ice sheet presumed to have existed during the last glacial maximum, have yet to be verified in West Antarctica. At present, it is not known what role englacial properties might play in initiating ice streams.

Knowledge of the englacial properties as well as data of the lithology, thermal regime and isostatic adjustment at the ice-rock interface can only be obtained by comprehensive geophysical investigations supported by direct measurements in holes drilled through the ice. Geophysical studies need to be conducted throughout West Antarctica and should include gravity and magnetics surveys combined with measurements of the englacial and subglacial morphology using ice-penetrating radars as well as active and passive seismic experiments.

4.5 Connections with Other Research Programs

Much of the research necessary for the attainment of the SeaRISE goal is already being supported or planned under the auspices of other active programs. This section describes the connections and overlaps that exist between SeaRISE and other projects or programs. Reports describing each of these projects have already been written. Appendix A reproduces the Executive Summaries from each report and indicates where the full report can be obtained.

4.5.1 Siple Coast Project

The Siple Coast Project (SCP) is a glaciological study concentrating on that portion of the West Antarctic ice sheet which drains into the Ross Ice Shelf (SCP Steering Committee, 1988). It aims to determine both the current mass balance of this region and the physical controls on ice flow in this region, and to predict the future behavior of the region. While the first two goals are well in hand, it has become increasingly apparent that the prediction of the future of a marine ice sheet is not solely a glaciological problem. It requires an understanding of the complex nature of interaction between the ice, the underlying lithosphere, the ocean and the atmosphere. It requires the understanding that SeaRISE is designed to provide.

In turn, the SCP has discovered the significant changes in the ice sheet which form the urgent basis for SeaRISE. Along with the discovery of major mass

imbalances and changes in ice velocities, SCP investigators have revealed the existence of a thick, extensive subglacial layer whose mechanical properties are probably responsible for the rapid motion of the ice streams.

According to the SCP Science Plan (SCP Steering Committee, 1988), the major field activities are expected to terminate by 1993 and would probably not overlap with new SeaRISE investigations.

4.5.2 Antarctic Geophysical Initiative

The Antarctic Geophysical Initiative (AGI), scheduled to begin in 1990, is a 10-year program that will focus on understanding the tectonic evolution of Antarctica and discerning the role of Antarctica in paleoenvironmental change that culminated in the Cenozoic glaciation (Workshop Report on the Antarctic Lithosphere, 1988). The initial thrust of this program will be in West Antarctica. All of the geophysical data collected as part of the AGI will contribute to the objectives of SeaRISE and, similarly, the geological and geophysical undertakings of SeaRISE will contribute to a better understanding of both the tectonic evolution and paleoenvironmental history of West Antarctica. It is expected that the two programs will ultimately share many of the same participants and that their common scientific and geographical focus will result in close cooperation.

4.5.3 Global Ice Core Research Program

The Ice Core Working Group (ICWG) has identified the West Antarctic ice sheet as the location for a deep and intermediate coring program following the completion of the Greenland Ice Sheet Project-2 (GISP2) hole (ICWG, 1989). The primary goals of the West Antarctic phase of this program are: to determine the response of the West Antarctic ice sheet to the warmth of the last interglacial; to reconstruct a high-resolution, multi-parameter history of the ice sheet and the overlying atmosphere; and to elucidate the interaction between climate, ice sheet size, and sea level. Comparison of this record with that from GISP2 should allow assessment of the critical timing and phase relationships of global environmental changes affecting both Greenland and Antarctica.

The deep-coring program is being proposed along the ice divide in West Antarctica, a region where interests from the AGI and SeaRISE merge. The site selection for the planned deep and intermediate cores will clearly draw heavily on the wealth of data already collected by the SCP and eventually by the AGI and SeaRISE. The requirement of the coring program to know basal topography, current net balance, and 10-meter temperatures can be satisfied with SCP and AGI data. More information is required, however. Also desired are confirmation

of a frozen bed, local ice flow and meteorological sensitivity at the drill site. The first and third of these are addressed by SeaRISE.

It is thus clear that significant overlap exists between the goals of the ICWG and those of SeaRISE. Foremost among these is the concern to understand the interactions between the ice sheet and its environment. Ice cores from several of the West Antarctic ice-sheet localities recommended by the ICWG initiative contribute directly to SeaRISE. Examples include Ridge B/C and Siple Dome (see Map). It may be most appropriate that these drilling and analysis programs proceed under the auspices of SeaRISE with the scientific and analytical support of the ice-core community. It is likely that a close cooperation will develop between the two programs.

4.5.4 International Geosphere-Biosphere Program

The International Geosphere Biosphere Program (IGBP) is, as its name implies, a program with an international base, and its focus is the entire Earth. Recently, the Scientific Committee on Antarctic Research (SCAR) appointed a Steering Committee to define the role of SCAR research in the IGBP. That committee identified a number of ongoing or planned programs that would contribute to the aims of the IGBP. These included studies of sea-ice/ocean/atmosphere interactions, the interaction of the Antarctic ice sheet and sea level, and the Antarctic paleoenvironmental record (see Section 5.3). All of these are elements of SeaRISE and indicate the very useful contribution to the IGBP by SeaRISE.

4.5.5 Antarctic Programs of Other Nations

Many other nations have been active in research on West Antarctica and are concerned about the potential of rapid sea-level rise. Those most active are the United Kingdom, West Germany, Norway, and the Soviet Union. These four countries have joined together in the Filchner-Ronne Ice Shelf Programme (FRISP) directed at determining the current behavior and dynamics of the ice-sheet/ice-stream/ice-shelf system which feeds these two ice shelves (see Map). While the research of the FRISP is limited to glaciological and oceanographic studies, the area of interest includes a major portion of West Antarctica, and close cooperation with these scientists will be actively pursued by SeaRISE scientists.

There are also a number of countries conducting research in the Antarctic Peninsula under the Glaciology of the Antarctic Peninsula (GAP) program. The record of past ice-sheet configuration, oceanographic characteristics, and atmospheric circulation patterns produced by GAP researchers will be of obvious relevance to SeaRISE investigations. SeaRISE will maintain open communication

with these other programs to keep them informed of planned investigations and important results, and to facilitate collaborations between investigators that will benefit each program.

4.5.6 Satellite Programs

The suite of upcoming satellites will markedly improve the coverage of the polar regions. This is particularly advantageous for research in West Antarctica, most of which lies poleward of 75 degrees south. Many satellite sensors (e.g., passive microwave, visible and near-infrared imagers and radar altimeters) have been utilized extensively for monitoring of sea-ice cover and viewing details of ice-sheet surface topography. Many more applications of these data will surely follow (Thomas and others, 1985).

Another sensor that will become more useful is the synthetic aperture radar (SAR). Beginning with ERS-1, scheduled for launch in 1991, a series of satellite-borne SAR's will provide continuous coverage well into the next century.

Also new is the laser altimeter/ranger. This instrument will open up a new area of ice-sheet research. It will provide surface elevations far more accurate than has been possible with the established radar altimeter, and in ranging mode it will be able to measure the velocities and deformations at locations where laser retroreflectors have been placed. The Geodynamics Laser and Ranging System (GLRS) scheduled as part of the EOS satellite program is scheduled to be launched in the latter half of the 1990's.

4.6. Feasibility

None of the research in SeaRISE requires major technical advances; most of the capabilities are currently available in the United States. With the recent demonstration of ice-drilling expertise for both recovery of core and bed access, as well as the emphasis on new geophysical platforms, any part of the West Antarctic can be investigated either directly or remotely. Upcoming satellite programs will ease the collection of reconnaissance data. The laboratory capabilities also exist, as do the computers and modeling expertise to utilize them. With the proper funding commitment from national agencies, the goal of SeaRISE can be achieved.

To avoid impossible requirements of logistic support, SeaRISE field work will be organized so that field parties will work in the same general area at the same time. This has obvious scientific benefits as well, as both the SCP and AGI have already recognized. The area of the Ross Sea Embayment is the most probable candidate to initiate SeaRISE-coordinated activities. This expectation is

based on both logistic and scientific considerations. Logistically, the area is the part of West Antarctica closest to McMurdo Station. Scientifically, it is this area that has been most studied by glaciologists, geologists and oceanographers. Accomplishing the objective of SeaRISE (determining the current state, internal dynamics, interactions, and history) of this portion of the West Antarctic ice sheet would be a major achievement, and go far in determining the potential for marine ice sheets to rapidly raise global sea level.

4.7 Working Group

At the conclusion of the initial SeaRISE workshop, a working group was established. This working group provides a work force to promote the importance of the SeaRISE goal and objectives in the scientific community and plan future activities that will help make the project a reality. The members of this working group are listed at the beginning of this document. The present membership includes representatives from the ICWG (Grootes, Alley), SCP (Alley, Bindschadler, Blankenship, Kamb, and MacAyeal), and AGI (Blankenship).

4.8 Plan of Action

As discussed above (Section 4.6), the logical theater in which to initiate SeaRISE is the Ross Embayment region, from the ice divide in West Antarctica to the edge of the continental shelf in the Ross Sea. The scientific rationale for this is based on the wealth of data that have already been collected. What is lacking, however, is an interdisciplinary analysis of these data.

SeaRISE should begin by assimilating the data of the Ross Embayment area that already exist. This will be completed most effectively by hosting a scientific workshop attended by those intimately knowledgeable of the collected data and/or keenly interested in participating in SeaRISE. The object of this workshop will be to present the current knowledge of the Ross Embayment, to identify which key questions can be answered now, to indicate what additional data are required to answer the remaining questions, and to formulate a coordinated program of investigations to obtain those data and complete the required analysis. To be meaningful, the meteorological analysis will need to extend over the full West Antarctic ice sheet.

This workshop needs widespread publicity to ensure the participation of prominent Antarctic scientists. Such a workshop would be organized and hosted by the SeaRISE Working Group, sponsored by NSF/DPP, and should be held within the next year at a time when leading Antarctic scientists can attend. The final product would be a recommended program of investigations whose end result will be the attainment of the SeaRISE goal, predicting the marine ice-sheet

contribution to rapid sea level change, for this portion of the West Antarctic ice sheet.

It is anticipated that the program in the Ross Embayment would require 5 years. It is hoped that the workshop participants could also outline investigations appropriate for studies of the other marine ice-sheet areas in both West and East Antarctica (see Map), so as not to ignore these areas on the grounds of logistical difficulty and the focus on the Ross Embayment. There are arguments suggesting that the Pine Island and Thwaites Glaciers areas might be the most unstable portion of the West Antarctic ice sheet. Thus, there needs to be some reconnaissance work done in these other areas concurrent with the concentrated studies in the Ross Embayment. Following the first 5 years' work, it might prove most efficient to then shift the region of emphasis to one or more of these other areas of marine ice sheet which preliminary data suggest holds the greatest potential for contributing to rapid sea-level rise. It is probable that intense studies of these other regions would require another 5 years.

4.9 Budget

The SeaRISE Working Group estimates that the required support for the initial 5-year study would be \$1.0 million per year for each subject discussed in Section 4.4 (ice dynamics, ice cores, geophysics, oceanography, and meteorology) or \$25 million over the 5-year period. This funding is in addition to funds already required for AGI and the coring programs. However, as coordination and collaborations with activities in these programs are clarified, there could be a number of joint efforts where substantial savings in the overall cost could be realized.

5. SUPPORTING STATEMENTS FROM SCIENTIFIC PANEL REPORTS

Concern about ice-sheet collapse raising sea level is not new. Research on this critical subject has been identified and endorsed by many panels of distinguished Earth scientists. By taking a multidisciplinary approach, SeaRISE satisfies many separate research elements ranked as priority research by these panels. What follows are statements supporting the SeaRISE goal excerpted from these reports.

5.1 Our Changing Planet: The FY 1990 Research Plan. The U.S. Global Change Research Program, Interagency Committee on Earth Sciences, 1989

"High Priority Research Needs:

Ice Sheet Mass Balance. The most important area of research in the cryosphere is to determine the mass balance of the ice sheets...and determine how their respective mass balances are changing...because of the linkage of negative mass balance in glaciers to rising sea level [p. 36]...

Sea Ice and the Oceans. The dynamics and thermodynamics of the interaction between sea ice and the ocean and the influence of sea ice on both ocean circulation and climate require further study [p. 36]...

Ice-Ocean-Atmosphere Coupling. Much improved models are needed to link climate change to glacier mass balance changes and changes in sea level, so that the glacial component of sea-level change can be predicted. In addition, second generation, three-dimensional ice-sheet models, which include thermodynamics, ocean coupling, and feedback effects of solid Earth deformation, are needed to simulate the present state of the polar ice sheets and to predict the response of ice sheets to climate change. A better model of a marine-based ice sheet, such as the West Antarctic ice sheet, is needed to produce a coupled glacier ice-ocean-atmosphere model [p. 39]."

5.2 Earth System Science, A Closer View, Earth Systems Sciences Committee, NASA Advisory Council, 1988

"Interactive ocean-atmosphere-ice models..." are identified as an important research focus for studying the Earth system on time scales of decades to centuries (p. 152).

The following parameters are listed as providing a fundamental description of the Earth (Tables 9.1A and 9.1B):

<u>Importance</u>	<u>Parameter</u>
Essential	Ice Volume and Extent
High	Sea Level
Substantial	Ice-Sheet Surface Elevation
	Ice-Sheet Volume Changes

5.3 The Role of Antarctica in Global Change, Scientific Priorities for the International Geosphere-Biosphere Program (IGBP), Scientific Committee on Antarctic Research (SCAR) Steering Committee for the IGBP, (1989)

"Tasks that must be included in an Antarctic component of the IGBP include:

To monitor the rate and extent of change in the Antarctic sea ice, atmosphere, ocean and biota, and study their interactions;

To establish a system to measure changes in Antarctic snow accumulation and ice flow likely to affect ice mass balance and sea level;

To clarify further the past global environmental changes using deep ice cores and sediment records from Antarctica [p. 5]."

5.4 Glaciers, Ice Sheet, and Sea Level: Effects of a CO₂-Induced Climatic Change, Committee on Glaciology, Polar Research Board, National Research Council, 1985

"The physics of the dynamic response of the ice sheets to variations in climate is known in general terms, but some processes are not well understood or have not yet been incorporated fully in numerical models. Major gaps in understanding concern basal sliding, the coupling of ice streams with the ice sheets in which they are embedded, and what determines the position of the seaward (calving) face of ice shelves [p. 3]...

In the case of the West Antarctic Ice Sheet, the situation is further complicated by the possibly delicate stability of the interaction between ice streams and ice shelves. If melting from the base of ice shelves were to increase markedly, the effect on ice streams could be far more important than the expected minor increase in surface melting and runoff [p. 4]."

5.5 Environment of West Antarctica: Potential CO₂-Induced Changes, Committee on Glaciology, Polar Research Board, National Research Council, 1984

"It has been suggested that a rapid reduction of the ice mass of West Antarctica leading to a drastic rise in sea level might occur as a consequence of CO₂-induced warming.

The existing West Antarctic environment is inadequately described by the available observations. This conclusion holds both for the general atmospheric and oceanic circulations and for their specific manifestations: the mass and energy balances of the inland ice sheet, the ice shelves, and the surrounding sea ice [p. 1]."

"This rise in sea level [caused by a rise in CO₂] will be relatively manageable in the next century unless, as some scientists have suggested, the warming triggers a rapid reduction in the ice mass of the West Antarctic Ice Sheet. In order to assess the possibility that this would happen, two kinds of studies are required. First, the external climate factors that influence the West Antarctic Ice Sheet--mainly precipitation, summer temperature, and oceanic heat flux--need to be known. Second, the dynamic response of the ice sheet/ice stream/ice shelf system to changes in this external forcing needs to be understood [p. 4]."

5.6 U.S. Research in Antarctica in 2000 A.D. and Beyond, A Preliminary Assessment, Polar Research Board, National Research Council, 1986

"OUTLOOK BEYOND 2000 A.D.

...the scientific priorities for antarctic research will most likely reflect the global issues of pollution, climate change habitability, resources, geotectonics, and other large-scale problems.

Examples of just a few of the many specific global questions that may be addressed include the following:

- * The stability of the West Antarctic Ice Sheet in the face of the anticipated global warming...
- * The role of the Antarctic in forcing the global atmosphere and ocean...
- * The intensity of the antarctic-driven forcing system, the parameters that control it, and its fluctuations with time [pp. 13-14]."

"Glaciology's recent exciting discoveries and advances are expected to continue with regard to understanding the role of ice in climate, documenting the

climate of the past, determining the stability of the ice sheets, and assessing the potential future impact of the antarctic ice sheet on sea level [p. 21]."

5.7 Antarctic Solid-Earth Sciences Research: A Guide to the Next Decade and Beyond, Ad Hoc Committee on Antarctic Geosciences, Polar Research Board, National Research Council, 1986

"The following are the most important broad topical problems...that we recommend be investigated during the next decade of Antarctic geoscience research: ...

Category A: Antarctic Problems with Global Implications [p. 8]. ...

3. The reconstruction of a more detailed history of the Antarctic Ice Sheet and the definition of the physical, geological, and biological responses to it on both the regional and global scale [p. 9]."

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Appendix A: Executive Summaries of Related Research Programs

A.1 SCIENCE PLAN FOR THE SIPLE COAST PROJECT

EXECUTIVE SUMMARY

The project described in this document is the first systematic field and theoretical study of the stability of an ice sheet. The issue of ice-sheet stability is of premier importance in view of the demonstrated sudden decay of former ice sheets and the prospect that the west antarctic ice sheet may follow suit. As with prior events, a collapse would have global impacts on climate and sea level. The west antarctic ice sheet is the remaining ice sheet that is considered most prone to change, and this change could be induced naturally or triggered anthropogenically through such events as a greenhouse warming.

The portion of the west antarctic ice sheet that flows into the Ross Sea (across the Siple, Gould and Shirase Coasts) has been selected for a large, carefully coordinated study of icesheet stability. This region is known to be changing currently, and to have undergone major changes in the very recent past. It is also logistically accessible and the weather is generally good for field work.

The Siple Coast Project is driven by the need to understand the extent to which the west antarctic ice sheet may change and affect climate and sea level. This entails the following goals:

1. to determine the configuration and mass balance of the part of the west antarctic ice sheet that feeds into the Ross Sea;
2. to determine the physical controls on ice flow; and
3. to predict future changes in the ice sheet.

These goals are ambitious, yet achievable, and they directly address major unsolved problems in glaciology and climatology. Also, although only the portion that flows into the Ross Sea is being studied directly, the results can be extended readily to all of the west antarctic ice sheet and to other ice sheets.

The Siple Coast Project builds on the recent development and application of new techniques (especially satellite tracking, repeat photogrammetry, digitally recording seismic and radio-echo sounding, and hot-water drilling), and the understanding gained from prior, more-limited programs on the ice sheets of Antarctica and Greenland. As a result of this and of more careful experimental design, the Siple Coast Project stands at a considerably higher level of sophistication than prior programs in ice-sheet dynamics.

Executive Summary (cont'd.)

Many very important results have been obtained already. The suspicion that ice stream C has stopped, probably about 200 years ago, is confirmed. Ice stream B is changing irregularly and the region around Crary Ice Rise is thickening. Ridge A/B is very anomalous and indicates recent change. For ice stream B, the mechanical controls act mainly at the bed and not the sides, and the bed is lubricated by a slurry of debris and water. These early results demonstrate the unsteady condition of the west antarctic ice sheet and indicate the specific issues that need to be addressed next.

A detailed field schedule for accomplishing the goals of the Siple Coast Project is included here. According to this schedule, the field-work portion of the project should be largely completed by 1993.

Deep core drilling is the only phase of the Siple Coast Project that has not been initiated. This has been hampered by the uncertain availability of deep-core-drilling equipment in the U.S. This problem needs to be rectified.

A.2 A PLAN FOR A UNITED STATES PROGRAM TO STUDY THE STRUCTURE AND EVOLUTION OF THE ANTARCTIC LITHOSPHERE

EXECUTIVE SUMMARY

Antarctica is one of six major continental land masses on earth. The lithospheric plate of which it forms a part is one of seven major plates constituting the rigid shell of the planet. Thus it is an integral part of the earth's geodynamic system. Both the internal development of the Antarctic continent, and its changing relationship to the other continents of the former Gondwanaland supercontinent as the Antarctic plate grew, have played a central role in paleoenvironmental changes culminating in Cenozoic glaciation. Knowledge of the structure and evolution of the Antarctic plate is indispensable for global scale earth science. Moreover the Antarctic continent is an outstanding laboratory for studying certain specific tectonic processes of global significance.

In 1986 the Ad Hoc Committee on Antarctic Geosciences of the Polar Research Board* advocated a major change in the United States approach to Antarctic geoscience research. The Committee advised a more directed approach than heretofore, one involving a much greater utilization of new technology and concentrating certain types of research activity in a few geographic locations of prime importance. Specifically it identified three broad "Transect Zones," one each across the Weddell and Ross Embayments and one from the Amery Ice Shelf to the continental interior, as those holding the greatest promise for increasing our geological and geophysical understanding of the continent and hence the globe.

This document stems from the Workshop on the Antarctic Lithosphere convened in June 1987 to develop a United States scientific program to implement the main recommendations of the 1986 Polar Research Board report. It takes into account the current effort by the Scientific Committee on Antarctic Research of the International Council of Scientific Unions to develop a new international program to address problems concerning the structure and evolution of the Antarctic lithosphere that are likely to be beyond the capabilities of any one nation to resolve. The specific plan set out here, however, is for a United States program that can be mounted from US bases using logistics and platforms whose availability can reasonably be anticipated for a ten-year program accomplished by the year 2000.

In endorsing the concentration of geophysical activities in the Weddell, Ross and Amery transect zones, the Workshop participants identified the specific scientific problems that can best be addressed within each zone, including major problems of globally significant tectonic processes such as orogenesis and basin formation. The geophysical and geological programs needed to address the problems are identified as:

*Antarctic Solid Earth Sciences Research: A Guide for the Next Decade and Beyond. National Academy Press, Washington, D.C., 1986.

- Land geophysics - a new program of modern over-ice geophysical studies to address problems of the deep subglacial structure of the Antarctic lithosphere. These studies should include seismic reflection and refraction profiling along well-defined critical "corridors" within the broad transect zones.
- Corridor aerogeophysics - airborne magnetics, gravity, and radar sounding along closely spaced lines covering the area of the land geophysics corridors.
- Long-range aerogeophysics - airborne magnetic and gravity surveys of those parts of the Antarctic continental margin and adjacent oceanic lithosphere that are particularly inaccessible, because of their remoteness and/or ice cover. These measurements are needed to resolve outstanding questions of the kinematic history of the Antarctic and neighboring plates.
- Marine geophysical and geological studies - state-of-the-art seismic studies of the deep structure of the cordilleran orogen of the Antarctic Peninsula, the West Antarctic rift system in the Ross Sea Embayment, the Transantarctic Mountains front, the Amery Embayment and the diachronously rifted East Antarctic margin; also reconnaissance studies of poorly known marine segments of the transect zones.
- Topical outcrop geology - geologic studies to make full use of the scarce outcroppings of the Antarctic lithosphere in interpreting geophysical data and in resolving such problems as terrane displacements, uplift, and subsidence, as well as basic tectonic, igneous, and paleoenvironmental histories.
- Subglacial drilling -- to augment knowledge of Antarctic bedrock and thereby augment control of geophysical data interpretation in ice covered areas.
- Remote sensing -- analysis of satellite magnetic and gravity data as well as study of lithology and geologic structure using enhanced satellite imagery.

The emphasis on geophysical and structural/tectonic programs is not intended to down play the significance of other types of geologic study such as biostratigraphy and paleontology. It merely reflects the need for a new program directed at our understanding of the structure and evolution of the Antarctic continent as a whole, such as that envisaged in the Polar Research Board report.

A decade-long U.S. initiative is set out, and involves the following critical elements:

- Fielding of a continental geophysical and subglacial drilling program.
- Deployment of a long-range aerogeophysical aircraft.
- Alternate year deployment of a state-of-the-art marine geophysical vessel.
- Topical geologic studies deployed with flexible logistic support.

The plan submitted here clearly endorses the need for, and assumes the ability to provide, considerably greater direction in Antarctic earth sciences than in the past. Thus some change in management philosophy would be required for implementation. This does not mean close direction of the entire U.S. earth sciences program in Antarctica. Rather it means that the major components related to the transect zones study should be managed to the degree necessary to accommodate effective long-range logistic planning, budget development, and continuity of scientific effort. It is also necessary to ensure that the individual scientific components are coordinated and complementary. Two end-member management models are presented. In one, the Program Manager for Polar Earth Sciences acts with the advice of an Antarctic Geotraverse Advisory Committee (as recommended by the 1986 Polar Research Board report). In the other, a Steering Committee is assigned responsibility for detailed program planning, solicitation (as required) and screening of scientific proposals, and periodic submission of an omnibus-type proposal for peer review by a panel appointed by the Program Manager. The need for ensuring an open program of the highest quality cannot be overemphasized. The management would itself require periodic review regardless of the model adopted.

Finally, while the plan presented here is for a ten-year United States program it is recommended that U.S. scientists continue close involvement in the planning of an international program through the Scientific Committee on Antarctic Research. Coordination of U.S. efforts with those of other nations in addressing the problems of the Antarctic lithosphere could result in the sharing of logistic and scientific costs, the pooling of scientific and technologic expertise and data, and, most important of all, the ability to conduct studies beyond the capability of any single nation. The most pressing scientific problems identified by U.S. scientists and by the international community are virtually identical. With total open involvement of the U.S. community in the planning and execution of an international program of data acquisition, and with full participation of U.S. scientists in the analysis and interpretation of those data, the earth sciences, the United States, the Antarctic Treaty nations, and indeed the global community should all benefit.

A.3 U.S. GLOBAL ICE CORE RESEARCH PROGRAM, WEST ANTARCTICA AND BEYOND

1. Executive Summary

Developing to its full potential the paleoenvironmental information contained in the ice masses of the world requires a long-range program in which expertise from many different fields is focused on a common goal.

The US ice core research community proposes that the US drill several deep and intermediate cores in Antarctica and Greenland during the 1990s with the first deep core in West Antarctica. The relative timing of the changes in various core parameters in cores from the Arctic and the Antarctic will help us understand the dynamics of climate and global change. The West Antarctic core should reveal the response of the West Antarctic ice sheet to the warm interglacial climate about 125,000 years ago.

Expanded drilling and analyses of shallow cores in polar regions and at lower latitudes must complement the bipolar drilling program in order to document spatial variability in environmental change and to generate transfer functions to translate the long paleoenvironmental records from the Arctic and Antarctic into changes at lower latitudes.

To attain these scientific goals in a timely manner the Ice Core Working Group recommends that:

- NSF/DPP adopts a long-range ice core research plan and takes an active role in the realization of this plan by creating the infrastructure needed for vigorous and flexible ice core research.
- NSF/DPP manages and actively seeks funds to support the long-range ice core research program to ensure fair and open access for all members of the scientific community.
- NSF/DPP supports key non-core studies that are directly related to ice cores and are necessary to ensure proper site selection and interpretation of core data.
- NSF/DPP, together with other programs and agencies, encourages the development of innovative techniques for ice sampling and analysis that may improve the quality and/or reduce the cost of paleoenvironmental information from ice cores.
- NSF/DPP encourages scientists to optimize the data retrieval from all ice cores by analysis and interpretation of many different core parameters in multidisciplinary collaborations.
- A database for rapid drill site selection as well as a database of the results of core analysis be collected and made available via the World Data Center.
- Unused core sections be curated in a US ice core storage facility and be made readily available for additional studies to US investigators and investigators of countries with which the US has scientific collaboration and exchange of sample materials and research data.

A.4 SATELLITE REMOTE SENSING FOR ICE SHEET RESEARCH

EXECUTIVE SUMMARY

Despite 25 years of intensive field work in Greenland and Antarctica, and the expenditure of billions of dollars, we are still unable to answer the most fundamental glaciological question: Are the polar ice sheets growing or shrinking? However, the many detailed investigations during this period have identified three important aspects of ice-sheet behavior:

1. The ice sheets are continually changing. Although the ice is either thinning or thickening within most of the areas studied, we cannot determine whether the observed changes represent redistribution of mass within the ice sheets, or mass exchange with the ocean. To answer this question, we need data from all of the major catchment basins. The most straightforward approach to determining the rate of thickening or thinning (the "mass balance") is to measure periodically the surface elevation at many points on the ice sheet. This can be done only from satellites using a radar or laser altimeter.
2. The ice sheets and the global climate have a complex cause-and-effect relationship operating on time scales ranging from months to millennia. In addition to direct relationships such as those between air temperature and ice ablation, or precipitation and ice accumulation, there are many indirect and poorly understood linkages. For example, sea ice has a modulating effect on the source of moisture that feeds the ice sheets with snow; ocean circulation and sea-ice cover around Antarctica strongly influence melt rates from beneath floating ice shelves which, in turn, regulate ice discharge rates from the continent. In order to identify and investigate these various feedback mechanisms, we need to monitor a selection of critical ice parameters: summer melt zones; surface temperatures; precipitation rates; ice-surface elevations and the positions of seaward margins of the ice sheets; and sea-ice extent. Most of this information can be obtained only from satellites.
3. In the annual layers of deposited snow, ice sheets contain a unique record of world climate and atmospheric composition over the past several hundred thousand years. Interpretation of this record requires an understanding of ice-sheet dynamics. This is because samples within an ice core have been displaced from their original deposition sites, and they have been thinned by varying amounts depending on past ice-sheet

dynamics. A first step toward developing this understanding involves close analysis of present-day ice behavior which first must be described by a combination of global monitoring from satellites and detailed field investigations in areas of particular interest.

During the next 10 years, we shall have the opportunity to acquire data from altimeters; from visible, infrared, and microwave radiometers; scatterometers; and from Synthetic Aperture Radars (SARs) which will overfly the ice sheets. In order to assess potential research applications of these data and to determine which data should be acquired, NASA has asked a small group of glaciologists to address these issues. This report presents their recommendations, which the group believes to be representative of consensus opinion among the glaciological research community.

Actions recommended by the group can be summarized as:

- Surveys of ice surface topography by satellite altimeters should be repeated at intervals of approximately 5 years.
- Surveys of the seaward margins and near-coastal surface features of the ice sheets, using Landsat quality and/or SAR imagery, should be repeated every year.
- There should be long-term routine monitoring of ice-surface characteristics (temperature, accumulation rate, presence of surface melt) using infrared and passive-microwave radiometers for synoptic coverage and SAR for focused investigations of selected regions.

This research program will provide both the reconnaissance data that are sorely needed to describe overall ice-sheet behavior, and fundamental information on mass balance and environmental conditions that is essential to understanding present behavior and to the development of reliable predictive models. Results from this program will lead to more effective planning of *in situ* investigations by identifying areas that require focused study, and the interpretation of such intensive measurements from widely separated sites will be greatly facilitated by the overall picture of ice-sheet behavior provided by satellites.

We are on the brink of a major advance in ice-sheet research, and we must be ready to make effective use of the satellite measurements which will make this possible.

Appendix B: Addresses of Workshop Participants

APPENDIX B

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Report Documentation Page

1. Report No. NASA CP-3075	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle SeaRISE: A Multidisciplinary Research Initiative To Predict Rapid Changes in Global Sea Level Caused by Collapse of Marine Ice Sheets		5. Report Date May 1990
		6. Performing Organization Code 671
7. Author(s) R.A. Bindschadler, Editor	8. Performing Organization Report No. 90-077	
	10. Work Unit No.	
9. Performing Organization Name and Address Goddard Space Flight Center Greenbelt, Maryland 20771	11. Contract or Grant No.	
	13. Type of Report and Period Covered Conference Publication	
12. Sponsoring Agency Name and Address National Aeronautics and Space Administration Washington, D.C. 20546-0001	14. Sponsoring Agency Code	
15. Supplementary Notes		
16. Abstract This document reports the results of a workshop held to discuss the role of the polar ice sheets in global climate change. The participants agreed that the most important aspect of the ice sheets' involvement in climate change is the potential of marine ice sheets to cause a rapid change in global sea level. To address this concern, a research initiative is called for that considers the full complexity of the coupled atmosphere-ocean-cryosphere-lithosphere system. This initiative, called SeaRISE (Sea-level Response to Ice Sheet Evolution) has the goal of predicting the contribution of marine ice sheets to rapid changes in global sea level in the next decade to few centuries. To attain this goal, a coordinated program of multidisciplinary investigations must be launched with the linked objectives of understanding the current state, internal dynamics, interactions, and history of this environmental system. The key questions needed to satisfy these objectives are presented and discussed along with a plan of action to make		
17. Key Words (Suggested by Author(s)) Ice Sheet Climate Change Global Change Sea Level	18. Distribution Statement Unclassified - Unlimited Subject Category 42	
19. Security Classif. (of this report) Unclassified	20. Security Classif. (of this page) Unclassified	21. No. of pages 55
		22. Price A04

National Aeronautics and
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